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The transition to environmentally sustainable production: a roadmap timeline methodology

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Abstract

In this paper, a high-level methodology for the transition to environmentally sustainable practices in the manufacturing industry is developed. The methodology presented in this paper is at the conceptual level and is developed to be applicable to a wide array of industrial settings. The sustainability transitioning methodology provides decision-makers with a roadmap timeline for the methodical decision-making to adopt environmentally sustainable technologies and practices. This is accomplished through integrating two key tools for the selection of new technologies: the technology readiness level, and the ease of implementation versus the impact analysis. The proposed methodology informs decision-makers of the priorities and the perceived impact of the potential technologies. Test and validation are carried out with a case study from the United Kingdom's aerospace sector. Results from the case study revealed that applying the methodology could influence decision-makers to approve or dismiss the use of new technologies.

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Keywords: Environmental sustainability; TRL; Manufacturing; Roadmap

1. Introduction

With sustainability gradually becoming accepted as a key attribute of manufacturing systems (along with cost, flexibility, quality, and time) [1], it has become inevitable to integrate sound sustainability practices into manufacturing systems. With the increasing global interest in environmental sustainability, e.g. the United Kingdom's ambitious plan of achieving "Net Zero" by 2050, and a recently set milestone of reducing greenhouse gases (GHGs) emissions by 68% compared to 1990 rates by 2030, it is no longer an option for manufacturing enterprises to adopt environmentally sustainable practices, it has become a must.

The unforeseen onset of the global outbreak of the COVID-19 pandemic has had its adverse impact not only on the healthcare, retail, and services sectors, but it also outstretched to the manufacturing sector [2]. The impact of the COVID-19 pandemic on the environmental performance of the manufacturing sector, particularly manufacturing of non-essential items, might first seem positive due to lack of demand. However, a deeper probing into the relationship of environmental sustainability with the remaining two pillars of sustainability (i.e. economic and social) [3] reveals that this is an unlikely outcome. Past events that caused largescale slowdown in manufacturing activities (e.g. the 1970s fuel crisis, the 2008 financial crisis) showed a resurgence in

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manufacturing activities. Such resurgence can be exacerbated by some governments (e.g. USA and Mexico) decisions to temporarily relax some environmental regulations in their efforts to stimulate the post-COVID economy [4]. However, even in the scenario of interim relaxation of governmental environmental regulations, manufacturing enterprises that possess strategic vision will likely realise the need to commit to environmental practices sooner rather than later (e.g. due to depletion of non-renewable energy resources).

Having established the need to adopt sustainability practices in the manufacturing sector, the road to do so is not always straightforward. Many well-established and global manufacturing enterprises are indeed interested in transitioning to environmentally sustainable production, but lack a clear vision and a roadmap to do so [5]. In particular, the order of which environmentally sustainable technologies and practices to implement is often unclear. In order to maximise the benefits attained from adopting sustainable practices, relatively easy to implement practices, often termed 'low hanging fruits' can be adopted in the short-run whilst the organisation works on updating its infrastructure to adopt more fundamental practices. Therefore, an improvement of environmental performance is achieved while more substantial practices are under development.

Many models, frameworks and methodologies have been developed for the implementation of sustainability practices in different sectors. In [6], the authors proposed a framework for the design of sustainable manufacturing systems where they explicitly addressed the areas of sustainability performance measurement and organisational change. In [7], a framework that integrates systems thinking with LCA was developed for decision-aid at both the planning and production levels. Also a decision-making framework integrating LCA, environmental sustainability with traditional metrics with a multiple-criteria decision analysis has been developed in [8]. Although the contemporary literature is rich in research efforts dedicated to environmental sustainability in the manufacturing sector, a high-level methodology that aids in prioritising the adoption of sustainability-enabling technologies and practices is still missing. In this paper, a high-level methodology, at the conceptual level, for the adoption of environmentally sustainable practices in the manufacturing sector is presented. The methodology therefore contributes to facilitating the sustainability transitioning through bringing together different tools, from different disciplines, formally in a unified framework. The rest of the paper is organised as follows: Section 2 presents the proposed methodology, Section 3 presents a case study in the aerospace manufacturing sector where the transitioning methodology is adopted and, finally, in Section 4 the concluding remarks and future research directions are presented.

2. The sustainability transitioning methodology

The development of the sustainability transitioning methodology presented in this paper is based on a review of the contemporary literature on previous sustainability transitioning methodologies, tools and techniques used in previous studies, and on thorough discussions with industry leaders. Although the sustainability transitioning methodology is high-level and can be applied to any establishment, in the context of this paper it is applied to an industrial setting due to the adverse contribution manufacturing processes inflict on the environment. Before the application of the transitioning methodology, the desired aim sought from applying more sustainable practices should be explicitly set, and a timeframe for application should be established (e.g. achieve carbon neutrality in 10 years or reduce CO2 emissions by half in 5 years). The transitioning methodology, as depicted in Fig. 1 below, consists of five sequential steps as explained next. To apply the transitioning methodology in a systematic, reconfigurable, and reproducible way, it is necessary first to identify relevant Key Performance Indicators (KPIs). These KPIs are then used by the manufacturing enterprise as metrics to measure and benchmark its performance in the respective areas of desired improvement against established, clearly defined targets. The selection of KPIs is a critical task as it defines, and sets the stage for all subsequent stages and should be tailored to specific industrial settings. In fact, KPIs that reveal information about the environmental performance resulting from manufacturing activities could vary depending on the targets and the objectives set by the manufacturing organisation. Significant work has been already completed in defining sustainability-related KPIs. For example, the authors in [9] discuss different energy and material efficiency KPIs such as specific energy consumption (SEC) and operational material efficiency (OME). Other environment-specific KPIs include, but not limited to, amount of CO2 equivalent, solids released as process waste or into water sources [10]. In general, such KPIs could be related to energy consumption (e.g. system-wide total energy consumption, per product energy consumption etc.), or they could be more explicitly directly focused on the environmental performance (e.g. total CO2 emissions). When applying the methodology, care should be taken in evaluating the selected KPIs not only according to absolute figures, but normalising appropriately (e.g. to provide a better perspective in the events of seasonal production fluctuations or output variation) as although absolute figures are still important, in some cases they do not convey the full picture.

The next stage is to identify technologies and practices that could be adopted and implemented to improve the environmental performance of a manufacturing enterprise, or indeed any establishment, that aims to improve its environmental performance by adopting the sustainability transitioning methodology. At this stage, any technology and practice can be identified, with less consideration of the manufacturing enterprise's capability of implementing it. This stage, like all subsequent stages, is directly influenced by the nature of the KPIs identified in the preceding stage that enable a useful quantitative performance evaluation. The options that could be considered at this stage are plentiful, and they could be general (e.g. the typical replacement of incandescent light bulbs with LED lighting to reduce energy consumption) or specific to manufacturing processes (e.g. switching to new coolants that produce fewer waste). The identification of potential technologies/ practices is done mainly through literature review, companies' reports and white papers, amongst other resources, where best practices are identified. The selection process for the potential technologies and practices will become clear in the discussion of the next two stages.

After the KPIs and the potential environment sustainability enabling technologies and practices are identified, the next step is to assess the maturity of the identified technologies using a well-developed framework. For this purpose, the Technology Readiness Level (TRL) framework is used as a tool to provide decision-makers with understanding and potential risks associated with the new technologies. The TRL framework is a well-established method that has been developed by NASA in the 1970s and is adopted in several professional bodies such as the US Department of Defense [11] and the European Commission [12]. The TRL scale comprises nine levels of maturity starting from a basic principle being observed, up to the actual technology being successfully deployed in operational settings. For more information about the TRL scale, and how to assess the TRL of a given technology, the interested reader can refer to [11]. For the determination of each of the potential technology's readiness level, several approaches (or a combination of them) can be utilised. For the most part, an up-to-date literature review of the latest peer-reviewed published literature should suffice, particularly for the lower TRL stages (TRL 1 and 2), as they provide an underpinning, not the full picture. The contemporary literature is rich in studies that evaluate both emerging and well-established environmental sustainability enabling technologies. In the next section it will be shown that the validation of the proposed methodology follows a screening of the most recent peer-reviewed published literature and, if the relevant maturity level cannot be established reliably, expert judgement could be sought or a formal Technology Readiness Assessment (TRA) could be conducted [11].

Once the KPIs and the potential enabling technologies and practices are identified, and each enabling technology's TRL is determined, an ease of implementation versus impact matrix (e.g. Six Sigma PICK Chart) is developed. In the ease versus impact matrix, each of the potential technologies and practices is placed on a two-dimensional chart where the axes represent the ease of implementation and the perceived impact on performance to prioritise the downselection of options. The ease of implementation of technologies and practices is always a subjective aspect (e.g. cost, available infrastructure, top management willingness to change, etc.). The same principle applies to the determination of the perceived impact of adopting the technologies and practices on certain aspects of the performance. Therefore, there is no "hard and fast" rule that sets strict guidelines, particularly when considering that such need will typically target immediate needs. For the determination of the perceived impact on performance, timescales to deployment, recurring and non-recurring costs and system complexity are typical, but adaptable substantive measures. The function of this stage is to set the priorities for which technologies/practices to adopt first, and which should be postponed to the future. Therefore, there is a close interdependence between the previous stage (mapping of potential technologies to TRLs) and the determination of ease of use and the perceived impact of each technology. The previous stage determines which technologies are currently being used and proven to be efficient, and which require further validation (i.e. could be potentially implemented in the future when their usefulness is proven). Although the implementation of this process in the proposed transitioning methodology is a 'heuristic' one, formal implementation with scoring of each potential technology and practice for a more methodical decision-making is possible [13].

The final stage of the proposed methodology is to create a roadmap timeline based on the outcomes of the previous processes. The roadmap should naturally correspond to the timeframe set along with the goals at the beginning of the implementation of the methodology. Intuitively, technologies that have a high TRL number (deemed mature enough for implementation in the near future) should be the ones considered for implementation in the near future. The threshold of the TRLs to be considered for implementation should be determined by the manufacturing enterprise. Then, once the ease of implementation versus impact matrix is constructed, the priority for the available options is set. The roadmap timeline should ideally be divided into time horizons (e.g. enforce new practices such as switching the lights off when natural daylight suffices as an immediate implementation, or switching to clean renewable sources of energy as a long-term strategic goal).

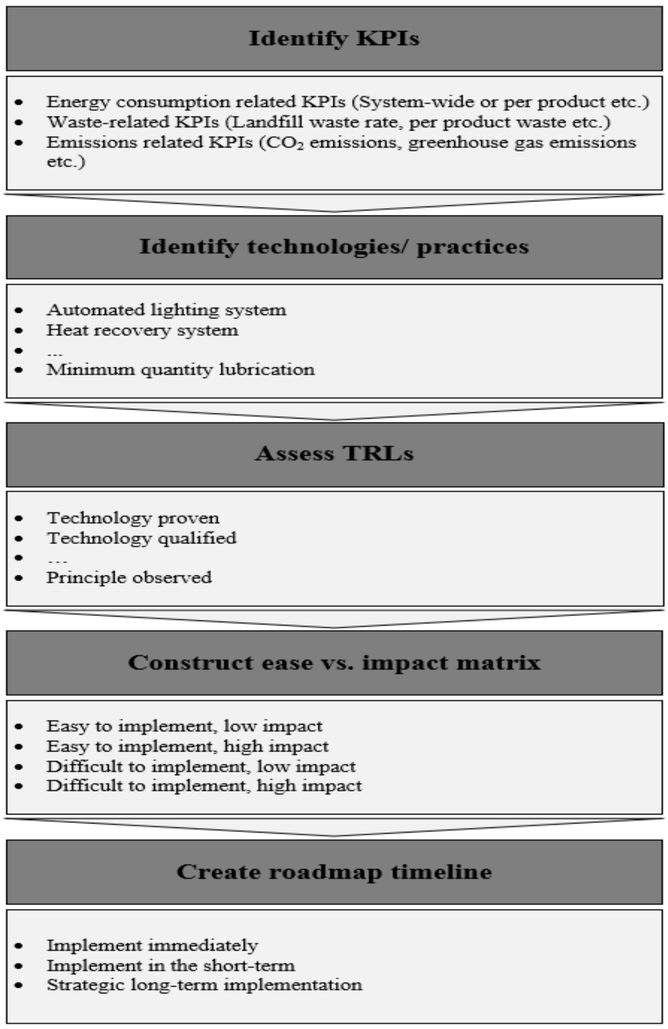

Fig. 1. The sustainability transitioning methodology

In order to validate the viability of the proposed transitioning methodology, a case study in the aerospace manufacturing sector is conducted in the next section.

3. Industrial case study

To establish the validity and the viability of implementing of the transitioning methodology in a production setting, a case study from the aerospace manufacturing sector is provided in this section. The validity of the transitioning methodology is established through thorough discussions with the leadership in the manufacturing enterprise where they were, based on the data provided, directly involved in the selection process of the proposed technologies/ practices. The leadership at the manufacturing enterprise were presented with the proposed sustainability transitioning methodology, along with the potential perceived gains from its implementation. Based on the evidence provided to the manufacturing enterprises' management (which was deduced from analysis of the contemporary literature, calculations and two of the coauthors' expertise in leading several EU and international projects on environmental sustainability), the proposed methodology was deemed valid for adaptation by the enterprise. The aerospace manufacturing enterprise is a Super Tier 1 aerospace part supplier and system integrator that is based in the United Kingdom and operates 43 production sites, and supplies aircraft and engine manufacturers all over the world. The company, although not new to sustainable practices, aspires to achieve an aim of net zero carbon dioxide emissions by the year 2030. Given the manufacturing enterprise's aim of CO2 reduction, CO2 emissions has been chosen as the KPI to measure against. Data that reports resources and energy consumption in one of their UK production sites for the years 2018, 2019 and 2020 were collected and analysed in order to identify where most resources are consumed, and what generates the most waste. In particular, for the purposes of this research paper, compressed air leaks, along with coolant usage and energy consumption for several processes data are analysed. In order to identify where more waste in generated, and hence where more energy and CO2 emissions are likely higher, Pareto analysis was performed as shown in Fig. 2 for a subset of the data for the year 2020.

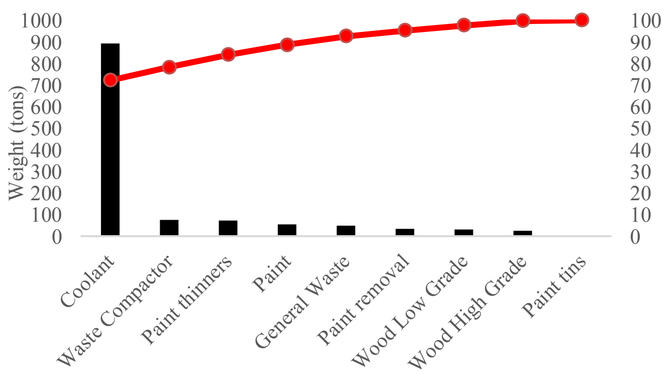

Fig. 2. Pareto chart for different types of wastes

Based on the analysis presented in Fig. 2, it is apparent that the majority of wastes, more than 70%, comes from coolant usage. The insight that this result provides will be apparent throughout the upcoming discussion and will impact the decision of which technology and practices to use and when to implement them.

First, to establish short-term practices that could lead to energy savings, the manufacturing enterprise was interested in general practices that it could implement immediately. For this purpose, the installation of automated lighting system was proposed. Indeed, such basic practices are often overlooked and, according to [14, 15], as much as 19% of electricity bills in industrial facilities could be consumed by lighting. To this end, the installation of automated lighting control system, powered by LED lights could save up to 40% - 60% of the electricity consumed by lighting [15, 16]. For example, the replacement of one 400W metal halide luminaire with another 200W LED yields an energy saving of approximately 208W, which, expressed at levels of reduction of CO2 emissions, corresponds to 85g of CO2 for each operating hour [17]. This reduction in CO2, although seems minimal, becomes substantial in large production facilities where all lighting is replaced with more energy-efficient alternatives. When assessed on its TRL, automated lighting control systems falls in the most mature technologies level (TRL 9) on the TRL scale [18, 19].

On a more advanced level, and remaining with the KPI of energy consumption, the manufacturing enterprise was presented with a proposal to replace their electric motors with premium efficiency electric motors. Electric motors are widely used in manufacturing operations. Most electric motors are designed and manufactured under the eco-design rules, which assist in ordering their energy-efficient classes (IE). IE is computed as the ratio between mechanical output performance and electrical consumption. There are four different classes depending on their efficiency namely, IE1, IE2, IE3, and IE4 [20]. For example, the IE4 Super Premium Efficiency motors can provide up to 20 % reduction in energy losses during their lifecycle comparing to Premium Efficiency IE3 motors [21]. The IE4 super premium efficiency motors are classified at the top level of technology maturity (TRL 9) at the TRL scale [21].

When the waste data were analysed, coolant was the highest contributor to waste, accounting to 76% of the total weight of all wastes as was presented in Fig. 2. Coolant waste alone, in 2020, was in the magnitude of several hundred tons. Although this figure is particularly (and expectedly) high, it represents coolant waste after the manufacturing enterprise had managed to reduce its coolant waste by 27% in the production site where the data were supplied. This reduction in coolant waste subsequently significantly reduces upstream emissions. In addition, energy consumption related to coolant waste amounted to 45% of the total energy consumption of waste. In order to address the significant waste resulting from the use of coolants, an expansion in the application of minimum quantity lubrication (MQL) usage has been proposed to the manufacturing enterprise. In MQL, a small amount of lubricant come in contact with the machine tool to provide the required cooling and lubrication. MQL, which is a TRL 9, uses much less than one liter of lubricant per hour [22], which is a substantial reduction compared to the over 100 litres per hour of lubricant used in flood lubrication [23], and atomizing the lubricant droplets needs specialised equipment. Due to the low amount of lubricant used in this method, the metallic chips produced during the process are almost dry and can be easily recycled [24]. The MQL improves surface finish, chip breakability, cutting forces, residual stress, and tool life, with surface roughness and cutting force decreased by 38 and 59 percent, respectively [25]. However, MQL is not a complete substitute to traditional wet cooling techniques, for example some metals (e.g. titanium) are difficult to machine and require wet cooling due to thermal issues [26]. In addition, the implementation of MQL in all processes will likely dictate the redesign of some machine tools [26]. Therefore, implementing MQL is not generally considered as an easy, immediately applicable practice.

Next, the total energy consumption resulting from the most energy-intensive processes was computed from the data provided. The manufacturing processes that were identified by the manufacturing enterprise as most energy-intensive are painting, anodising and heat treatment activities. Such energy-intensive processes typically produce heat waste which, if partially recovered, can be converted to electric energy or the heat recycled to perform other activities. If such a heat recovery system, e.g. Organic Rankine Cycle (ORC) which is assessed to have a TRL 9 score, is implemented, estimated savings reported in Table 1, are expected to be attained assuming 7% efficiency for painting and anodizing, and 10% efficiency for the vacuum furnace.

Table 1 Energy consumption and perceived savings in 2020 if an ORC system is installed

Manufacturing process	Energy consumption (kWh)	Perceived energy savings (kWh)
Painting	586,630	41,064
Anodising	503,622	35,253
Vacuum furnace	242,265	24,226

Compressed air data has also been analysed, and based on the analysis, it has been observed that throughout the years 2018 – 2020, energy input for compressed air alone resulted in 20% - 30% of the total energy input. Data regarding the air leakages has been analysed and revealed that only 2% of the total wastes result from air leakages, therefore air leakages did not present a priority in the short-term.

Based on the analysis and the results obtained from the previous section, an ease of implementation vs impact analysis can be next conducted as depicted in Fig. 3 below, which is divided into quadrants to better convey the ease of implementation with respect to impact with respect to CO2 emissions visually.

It can be noticed from Fig. 3 that the easiest technology and practice to adopt is the installation of an automated lighting system, although its overall perceived impact could be low given the prevalence of such LED-powered systems adoption across industry. The easiness of implementation is, however, a subjective matter and, as discussed earlier, is determined by many factors (e.g. cost, available infrastructure, resistance to change, etc.) that could differ amongst adopting enterprises.

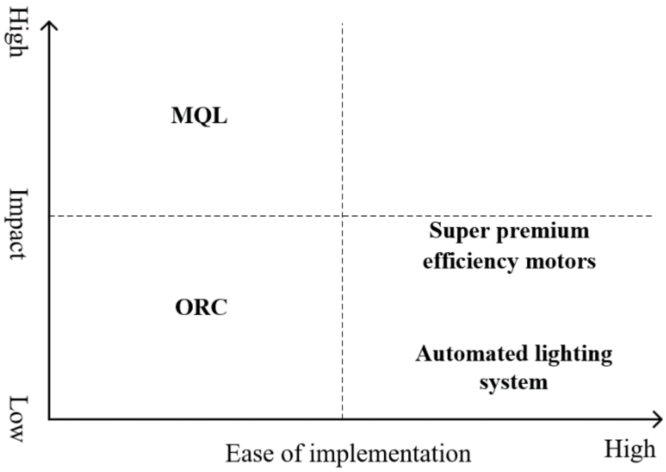

Fig. 3. Ease of implementation vs impact analysis

On the other end of the spectrum, the installation of an ORC system requires substantial investment and yields relatively modest energy and CO2 emissions savings as depicted in Table 1. Based on the analysis provided, the manufacturing enterprise dismissed the idea of implementing ORC for the short-term, instead of generating relatively modest amount of electricity from captured heat waste, they expressed interest to switch to energy suppliers of renewable resources. Indeed, the next phase of this research involves, amongst others, an evaluation of the United Kingdom's grid network capability of supplying all the manufacturing enterprise's UK factories with energy produced from renewable resources. In addition to the automated lighting control system, which the manufacturing enterprise intends to implement immediately, it intends, as a next step in the medium-term deployment, to invest in IE4 super premium efficient electric motors and MQL. Although not as easy to implement as the automated lighting system, these two technologies can directly affect energy and resource intensive processes and hence reduce energy consumption and CO2 emissions. The final roadmap that emerged from this research is presented in Fig. 4.

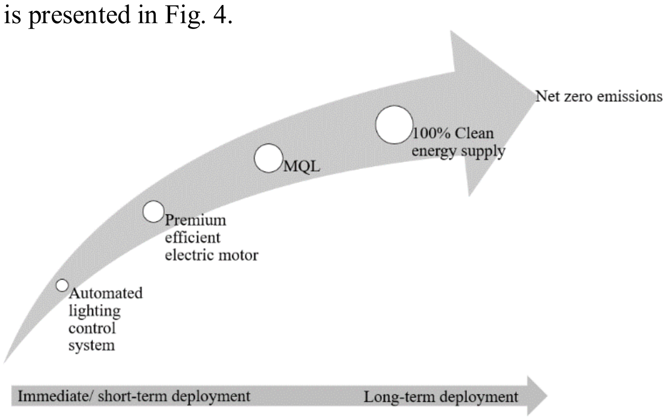

Fig. 4. The sustainability transitioning roadmap

4. Conclusion

The methodology presented in this paper, which is at the conceptual level, provides decision-makers in manufacturing enterprises with a better understanding of the technologies and practices that could improve the environmental performance of their organisations. The key advantage of the proposed transitioning methodology is enabling the prioritisation of the technologies and practices to adopt based on their maturity, ease of implementation and perceived impact on the environmental performance. The transitioning methodology has been applied to an industrial case study in the aerospace manufacturing sector. Implementing the transitioning methodology has been of particular importance in the case study as the manufacturing enterprise, in the production site where the case study was conducted on, was able to dismiss the immediate implementation of a technology, ORC, that it had been considering.

This paper represents the first (pilot) phase of a project about the transitioning to sustainable manufacturing that covers all three pillars of sustainability (i.e. environmental, economic, and social). The next phase of the project will consist of the development of lifecycle analysis (LCA) models for the proposed sustainability-enabling technologies, integrated with a decision-making framework that consists of mathematical programming and simulation model in a unified framework. The resulting framework will have a multi-criteria decision-making (MCDM) module that will quantify and evaluate the conflicting attributes of manufacturing systems and generate a set of optimal solutions that balances the trade-offs between the conflicting attributes. The next phase will also contain a formal analysis of more parameters such as compressed air leakage and potential upgrade of advanced control systems.

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